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# Overland Flow Directs Soil Moisture and Ecosystem

## Processes at Patch scale in Mediterranean Restored Hillslopes

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## **Abstract**

Semiarid and arid environments are frequently structured in vegetation patches that heterogeneously distribute water resources (water runoff and soil moisture). This redistribution is interrelated with episodes of rainfall triggering pulses of plant growth according to the Trigger-Transfer-Reserve-Pulse (TTRP) model. Spatial heterogeneity in the hydrological behaviour of surface patches has been described in Mediterranean mining restored hillslopes. Nevertheless studies describing the interactions of this hydrological heterogeneity with ecological processes on restored environments are lacking. This study investigates the relationships between overland flow running at hillslope scale and ecosystem processes at patch scale in restored hillslopes. We selected three approximately 20 year old restored hillslopes along a gradient of overland flow (hillslope runoff coefficients are 15.9%, 2.2% and 0.3% for the three experimental hillslopes). We studied environmental conditions describing the ecohydrological interactions under the TTRP approach for arid and semiarid environments. Our results indicate that in restored hillslopes: 1) soil moisture content was associated to the type of vegetation patches; 2) higher soil water content enhanced vegetation diversity and soil properties, improving vegetation performance and colonization opportunities; 3) there was an inverse relationship between the volume of overland flow and soil moisture at the hillslope scale, influencing, in turn, ecohydrological processes at the patch scale. Overall our results highlight the importance of overland flow modifying soil moisture distribution at patch scale and hence, influencing vegetation dynamics and ecological succession in these novel ecosystems.

**Keywords:** ecohydrology, mining, restoration, runoff, germination, facilitation.

## 1. Introduction

In semiarid environments, where water is the main limiting factor, a strong interrelation between vegetation and hydrology has been widely described (2005; Tongway et al., 2001). Frequently, these ecosystems are structured in different vegetation patches that distribute water resources heterogeneously (Cammeraat and Imeson, 1999; Cerdà, 1997a; Ludwig et al., 2000). Particularly, Mediterranean hillslopes behave as a patchwork of runoff-generating (sources) and run-on-capturing (sink) areas, where the size of the runoff and run-on patches highly depends on climatic conditions (Calvo-Cases et al., 2003; Lavee et al., 1998).

The heterogeneity of runoff generation and routing processes in restored hillslopes from opencast coal mining has also been described in Mediterranean-continental environments (Nicolau, 2002). Overland flow has been identified as a significant driving force for vegetation dynamics in these restored hillslopes, where the existence of steep berms generating runoff at the top of the slope is frequent (Hancock and Willgoose, 2004; Moreno-de las Heras et al., 2008). When the magnitude of overland flow exceeds a threshold, vegetation recovery is dramatically constrained (Espigares et al., 2011) and accelerated soil erosion processes arise, being rill erosion the most characteristic phenomenon (Moreno-de las Heras et al., 2010). Rills efficiently drain runoff away from hillslopes, reducing rainfall infiltration, and thus increasing water deficit (Moreno-de las Heras et al., 2010). As a consequence, vegetation dynamics become severely affected. It has been shown how seedling emergence, plant establishment and seed production are limited along a gradient of rill erosion (Espigares et al., 2011). Moreover, soil moisture content is spatially redistributed, being higher near rills, and lower on inter-rills. Moreno de las Heras *et al.* (2011) showed the link between the spatial pattern of the dominant species (*Medicago sativa*), and soil moisture

distribution in rills and interrills. When the amount of runoff routing downslope is low, overland flow is not directed by rills, running mostly as sheet flow. In these situations, the vegetation is able to establish on hillslopes forming a patchy mosaic structure. Merino-Martín et al. (2011) described the development of ecohydrological units (classified as runoff sources or sinks) where vegetation and hydrology are strongly associated in natural and restored hillslopes.

Feedback interactions between vegetation and hydrology in semiarid areas can be explained by the Trigger Transfer Reserve Pulse conceptual model (hereafter TTRP, Fig. 1) proposed by Ludwig et al. (1997). This framework states that densely covered vegetation patches obstruct runoff fluxes and store run-on, which promotes plant growth pulses. In turn, vegetation patches enhance soil infiltration capacity, which is considered a feedback mechanism. This model has been applied for the study of ecosystem functioning in both banded and patchy landscapes (Ludwig et al., 2005), and some evidences of the functioning of this model have been recently observed in an experiment in mine reclaimed areas in Mediterranean-continental environments (Espigares et al., 2012).

In this study, we explored the interactions between vegetation and hydrological processes both at the patch and the hillslope scale, along an overland flow gradient (i.e. three scenarios subjected to the routing of different amounts of overland flow). We used as a framework the TTRP approach to study the ecohydrological interactions. First, we compared soil moisture content in vegetation patches. Second, we analysed differences in specific ecological attributes between vegetation patches. Finally, we characterized the effects of vegetation patches on soil infiltration capacity and other soil properties in order to reveal potential feedback mechanisms. Our main hypotheses were: 1) Soil moisture content is associated to the type of vegetation patch (source or sink); 2) higher

93 soil water contents are associated to a better development of vegetation and soil  
94 properties. Specifically, we expected that higher soil water content in sink patches will  
95 enhance germination opportunities for plant species; 3) there is an inverse relationship  
96 between overland flow and soil moisture content at the hillslope scale that affects plant  
97 germination and colonization; thus the amount of overland flow routing along the  
98 hillslope influences hydrological processes at the patch scale.

99

## 2. Methods

### 2.1. Study area

This study was carried out in three reclaimed mining hillslopes located at *El Moral* spoil bank (40°47'50"N, 0°50'26"W, Fig. 1a). The spoil bank is located in the *Utrillas* coalfield (~1100 m above sea level) in the Iberian Mountain Chain (Teruel, Spain). The climate is Mediterranean-Continental with a mean annual temperature of 14 °C (ranging from a minimum mean daily temperature of 6.7 °C in December and a maximum mean daily temperature of 23.1 °C in July), with air frost period between October and April. Mean annual precipitation is 466 mm (mainly concentrated in spring and autumn) and potential evapotranspiration is 759 mm, yielding a hydrological deficit of 292 mm running from June to October. The local moisture regime can be classified as dry Mediterranean (Papadakis, 1966).

The three hillslopes were built between 1987 and 1988 by *Minas y Ferrocarril de Utrillas S.A.* mining company. They have a slope gradient of 20° and were covered with a layer of 80-100 cm of overburden clay-loam substratum. Revegetation of hillslopes was implemented after cross-slope ploughing by sowing with a mixture of perennial grasses (*Festuca rubra*, *Festuca arundinacea*, *Poa pratensis* and *Lolium perenne*) and perennial leguminous herbs (*Medicago sativa* and *Onobrychis viciifolia*). Although the hillslopes were restored using the same general procedures, they diverged in their subsequent evolution (i.e. rilling processes and vegetation development). The triggering factor causing these divergent trends is the difference in their geomorphological design: the different size of a barely covered (<5% cover) steep (40° slope) berm integrated at the top of the hillslopes that works as a water-contributing area (Moreno-de las Heras et al., 2009; Moreno-de las Heras et al., 2008). This steep berm



(Fig. 2a) generates important amounts of overland flow and has promoted the development of intense soil erosion processes, causing the formation of rill networks in one of the experimental slopes (Hillslope 1). Merino-Martín and others (2012) measured runoff in the experimental hillslopes for the hydrological year 2007-2008, showing an overland flow gradient from hillslope 1 to hillslope 3, with runoff coefficients of 15.9%, 2.2% and 0.3% respectively (see Appendix A). A detailed description of soil, cover, plant and erosion features of the hillslopes is presented in Appendix A.

In the aforementioned hydrological study, the authors identified seven types of vegetation patches or microsites (Merino-Martin et al., 2012) with different vegetation cover and composition that were characterized by a different hydrological behaviour. Vegetation composition in these hillslopes is the result of the combination of introduced species during restoration practices and colonization from surrounding areas along vegetation succession. Scattered clumps of (1) legumes (*Medicago sativa*) and (2) grasses (*Dactylis glomerata*) in a matrix of bare soil, and scattered dwarf shrubs of (3) *Santolina chamaecyparissus* and (4) *Thymus vulgaris* in a matrix of bare soil were identified as runoff sources. Patches densely covered by perennial grasses of (5) *Lolium perenne* and (6) *Brachypodium retusum* and by (7) shrubs (*Genista scorpius*) were identified as runoff sink patches. Since *Santolina* patches (3) were the only ones present at both ends of the overland flow gradient (hillslopes 1 and 3; Fig. 2b) soil moisture and seed bank traits in these patches were sampled twice (once in hillslope 1 and once in hillslope 3) in order to explore the consequences of overland flow volume routing along the hillslopes in the same patch. The remaining variables were only recorded once at *Santolina*, in hillslope 1, where the relative abundance of this vegetation patch was higher.

## 2.2. Field measurements

### 2.2.1. Vegetation and soil seed bank

In each type of vegetation patch, visual surveys of the presence of plant species were carried out in 15 randomly selected 50x50 cm quadrats to provide a fine description of vegetation features (floristic composition and richness). Presence of plant species was considered rather than abundance because in some patches the existence of two layers of vegetation (canopy and understorey) could influence results. Total vegetation cover was estimated in other 6 randomly selected 50x50 cm plots in each patch during the spring 2007.

In September 2007, before the arrival of the autumn rains, soil samples (38.5 cm<sup>2</sup> area × 4 cm depth) were collected in order to analyse differences in floristic composition of the soil seed banks in the different vegetation patches. Ten random samples were collected from each patch. Each of these samples was subdivided into four subsamples that were placed in 250 ml plastic containers over a 5 cm vermiculite layer. The floristic composition of the soil seed bank was determined after germination under optimal conditions in a greenhouse.

### 2.2.2. Rainfall simulations

Three rainfall simulations were carried out in each vegetation patch in the summer of 2008. Experiments were carried out using a single nozzle (HARDI® 1553) rainfall simulator based on the model described by Cerdà and others (1997b). Rainfall simulations were performed using a pressure of 2 kg cm<sup>-2</sup> over 0.24 m<sup>2</sup> plots with the nozzle placed 2 m above the soil surface and protected from wind effects with plastic sheets. Calibration under these conditions resulted in the following rainfall characteristics: rainfall intensity was 75.2 mm h<sup>-1</sup>; rainfall uniformity (sensu

Christiansen, 1942) was 72.94 %; drop diameter  $D_{50}$  (sensu Anderson, 1948) was 1.7 mm and mean terminal speed was  $4.0 \text{ m s}^{-1}$ , which implies a kinetic energy of  $13.4 \text{ J mm}^{-1} \text{ m}^{-2}$ . Rainfall intensity was selected in order to achieve a steady infiltration rate in patches with a dense vegetation cover. Natural rainfall of similar intensity during 30–60 min (range used for rainfall simulations) has a return period of 10–12 years in this area (Santamaría and Parrilla, 1999). The same intensity was selected in all the patches to allow following comparisons. Twenty-one steel rings (55cm diameter, 15 cm height) were installed (by inserting 5 cm into the soil) in the seven vegetation patches (3 in each; following Moreno-de las Heras et al., 2009). Each of these plots had a 2.5 cm diameter drainpipe outlet to collect runoff and sediments. Rings were installed in October 2007 in order to ensure natural consolidation of soil after surface disruptions caused during ring installation. The duration of each rainfall event was variable (until runoff rate was stable, lasting a minimum of 30 min). Runoff discharge in each rainfall experiment was collected manually at 1 min intervals, from the beginning of runoff. The volume of each 1 min sample was measured and accumulated in a plastic bucket. After each rainfall experiment, runoff samples stored in the bucket were mixed and a homogeneous aliquot (0.5 l) was extracted. Sediment concentration ( $\text{g l}^{-1}$ ) was determined in aliquots by weighing after oven drying ( $105 \text{ }^{\circ}\text{C}$ ). Time to runoff (min) was measured and runoff coefficient (%) was calculated. Finally, after each simulation, a vertical cut in the soil profile was used to measure the depth reached by the wetting front using a measuring tape (cm). This depth value was divided by the duration of the rainfall experiment to obtain the soil profile moistening rate ( $\text{cm h}^{-1}$ ). This measure, although not constant in time, can be used to make comparisons between the different vegetation patches on the vertical movement of water in the soil profile. To minimize the influence of water salinity on hydrological soil responses (Agassi et al., 1981) low

electrical conductivity and sodium absorption ratio water ( $EC=0.28 \text{ dS m}^{-1}$ ,  $SAR<1$ ) was used.

### 2.2.3. *Soil moisture dynamics*

To study the soil moisture dynamics in vegetation patches TDR (Time Domain Reflectometry) sensors were installed horizontally at different depths along the soil profile: 5, 25 and 50 cm, totalling four replicates in each vegetation patch. Soil moisture measurements were taken periodically (every 15 days without rain and within 5 days after each rainfall event) from April to December 2008. A TDR (Tektronix® 1502C) cable tester was used to collect the data, following the methodology proposed by Cassel *et al.* (1994), with an accuracy of 94 % in the determination of soil moisture.

### 2.2.4. *Soil properties*

Three composite soil samples (each sample formed by three homogeneously mixed subsamples, randomly distributed within each patch) were taken from the first 10 cm of the soil profile in each patch. Stoniness (%) was determined as the content of soil particles  $> 2 \text{ mm}$ . General physicochemical characteristics were determined using standardized methods (MAPA, 1994). A standard pressure chamber (Klute, 1986) was used to determine soil water content (%  $v/v$ ) at four different pressures ranging from saturation to permanent wilting point ( $\Psi=0$ ; -0.01, -0.03, -1.50 MPa). Parameterization of the soil water retention characteristic curves was made according to Van Genuchten (1980) from the samples collected in each vegetation patch. Additionally, soil bulk density ( $\text{g cm}^{-3}$ ) was determined in the upper part of the soil profile using fifteen unaltered soil cores (3 cm height x 5 cm diameter) collected in each vegetation patch, and soil surface strength was measured with a pocket penetrometer (Geotester®) in 15 randomly distributed samples per patch, four times per year (seasonal measurements in

summer - July, 30<sup>th</sup>-, autumn - October 27<sup>th</sup> -, winter - February, 15<sup>th</sup>- and spring - April 25<sup>th</sup>).

### 2.3. Laboratory measurements

#### 2.3.1. Seed germination under different water potentials

The hydrological requirements for seed germination in the eight most abundant species in hillslopes were studied (*G. scorpius*, *B. retusum*, *L. perenne*, *T. vulgaris*, *D. glomerata*, *S. chamaecyparissus*, *M. sativa* and *Aegilops geniculata*). For *M. sativa*, data obtained from a similar experiment carried out by our research group in the same study area (Moreno-de las Heras et al., 2011) were used. Seeds of *S. chamaecyparissus* and *A. geniculata* were collected in the field. As field seed collection of the remaining species was impractical because of low production, they were obtained from two local seed suppliers (Semillas Montaraz, S.A. and Zulueta Corporacion Para La Naturaleza, S.A.). *G. scorpius* seeds were scarified by submerging in sulphuric acid 95–98 % for 10 min following Bochet *et al.* (2007). Seed germination of each species was studied under eight different water potentials ( $\Psi=0$ ; -0.03; -0.10; -0.20; -0.33; -0.62; -1.10 and -1.50 MPa) representing a gradient of soil moisture between saturation and permanent wilting point. Water potentials were simulated using polyethylene glycol concentrations (PEG-6000) following the standard equations of Michel *et al.* (1983). Ten replicates per water potential were prepared. Replicates consisted of 15 seeds placed in a 9 cm diameter Petri dish, on a bed composed of a layer of hydrophilic cotton and filter paper. Replicates were moistened with 35 ml of distilled water (control;  $\Psi=0$ MPa) or PEG solutions ( $\Psi$  ranging from -0.03 to -1.50 MPa). To avoid water potential variations by evaporation, Petri dishes were sealed with PVC sheets. Petri dishes were placed in a phytotron under controlled conditions (day length= 12 h; air temperature= 20 °C;

relative air humidity= 75 %). Germination was monitored every three days; considering a germination when at least 2 mm of radicle emerged. The experiment lasted 46 days and then germination rate (%) of each species was calculated.

## 2.4. Data analyses

### 2.4.1. Vegetation and seed bank

Characteristic species for each vegetation patch were determined by applying Indicator Species Analysis (Dufrene and Legendre, 1997). We performed ANOVAs and Tukey *post hocs* to test significant differences in species richness and Shannon's diversity (vegetation and seed bank) between vegetation patches. Kruskal Wallis and Mann Whitney *post hoc* tests were used to analyse differences in soil seed bank density.

### 2.4.2. Rainfall simulations

Water infiltration was estimated as the balance between precipitation and measured runoff on a minute basis, and further fitted to the Horton-type equation proposed by Borselli *et al.* (1996):

$$I_t = I_f + (I_0 - I_f)e^{-\frac{pt}{K}}, \quad (\text{eq. 1})$$

where  $I_t$  is the instantaneous infiltration rate ( $\text{mm h}^{-1}$ );  $I_f$  is the final steady infiltration rate ( $\text{mm h}^{-1}$ );  $I_0$  is the initial infiltration rate ( $\text{mm h}^{-1}$ );  $p$  is the rainfall intensity ( $\text{mm h}^{-1}$ ),  $t$  is the time (h) and  $K$  is a coefficient which describes the shape of the apparent infiltration curve.

Differences in response parameters (the final infiltration rate  $I_f$ , the shape coefficient  $K$ , runoff coefficient, soil profile moistening rate, and sediment concentration) between vegetation patches were analysed by using ANOVAs and Tukey

*post hoc* tests for those cases in which parametric assumptions were satisfied, and Kruskal-Wallis and Mann-Whitney *post hoc* tests for non-parametric data.

#### 2.4.3. *Soil moisture*

We performed repeated measures ANOVA with soil water content data from vegetation patches, vegetation patch and sensor depth being the between-subject factors, and with time as the within-subject factor.

Soil water content was estimated at the hillslope scale (at 5, 25 and 50 cm soil depth) by considering the abundance (% surface cover) and soil moisture of each vegetation patch in each hillslope. A Friedman analysis with the Wilcoxon-Nemenyi-McDonald-Thompson *post-hoc* test was performed to compare the three hillslopes.

#### 2.4.4. *Relationships between vegetation traits and soil hydrology.*

We performed correlations to study relationships between vegetation characteristics (species richness, diversity and density of soil seed banks) and hydrological traits (infiltration parameters and soil water content) in each vegetation patch.

#### 2.4.5. *Soil properties*

Differences in soil bulk density between patches were tested by using ANOVA and Tukey's *post hoc* tests. For soil surface strength, the Friedman and Wilcoxon-Nemenyi-McDonald-Thompson *post-hoc* tests were used. The remaining soil physicochemical characteristics were tested using Kruskal-Wallis and Mann-Whitney U Test *post hoc* tests.

#### 2.4.6. Seed germination

A seed-germination sigmoid shape response function (Ahmadi and Ardekani, 2006) was fitted to the germination results obtained for each species:

$$G = \frac{G_{max}}{1 + e^{\frac{P - P_0}{b}}} , \quad (\text{eq.2})$$

where  $G$  is the germination rate (%),  $G_{max}$  is the maximum germination rate,  $P$  is the water potential (MPa),  $P_0$  is the threshold water potential value (MPa) below which the germination rate drops to zero, and  $b$  is a shape coefficient.

Threshold water potential values ( $P_0$ ) were transformed into soil moisture levels by using the (van Genuchten type) characteristic soil water retention curves that were parameterized for the different vegetation patch types. The obtained soil moisture threshold values were used to calculate the number of days suitable for germination in each vegetation patch throughout the year, or in other words, the days in which soil moisture at 5 cm depth was above the germination threshold value for each species in each vegetation patch during the two annual seed germination pulses (spring and autumn). A general temperature threshold of 10 °C (minimum temperature for seed germination) was also considered for calculations of the germination potential (Moreno-de las Heras et al., 2011). A “germination suitability index” (GSI) was determined by multiplying the number of suitable days for germination and the maximum germination rate for each species in each vegetation patch. Non-parametric bi-factorial ANOVA was applied to these data, with species and vegetation patch as factors and the germination suitability index as the dependent variable. At the hillslope scale, global GSI values were calculated considering the relative abundance (% cover) of each vegetation patch. Friedman analysis and *post-hoc* Wilcoxon-Nemenyi-McDonald-Thompson tests were applied to compare these values between the three hillslopes.



Indicator Species Analysis was performed with the PC-ORD package (McCune and Mefford, 1999). We used the R program (R\_Development\_Core\_Team, 2009) for the non parametric bi-factorial ANOVA (using the “adonis” function of the “vegan” package). The *post-hoc* Wilcoxon-Nemenyi-McDonald-Thompson test was performed with the “coin” and “multcomp” packages using the code of “Tal Galili”, published in r-statistics.com (<http://www.r-statistics.com/2010/02/post-hoc-analysis-for-friedmans-test-r-code>). The remaining statistical analyses were performed using STATISTICA 8.0 (Statsoft, 2001). Data analyzed using ANOVA and Tukey tests fulfilled parametric assumptions. The scientific names of the species are in accordance with *Flora Europaea* (Tutin et al., 1964-1980).

### 3. Results

#### 3.1. Vegetation and seed bank

A total of 54 species were identified. We found significant differences in species richness ( $F_{6,98} = 15.54$ ,  $p < 0.01$ ; Fig. 3) and vegetation cover (Kruskal-Wallis test  $H = 34.25$ ,  $p < 0.01$ ; Table 1) between vegetation patches. The “characteristic species” of each vegetation patch obtained with Indicator Species Analysis are shown in table 1. Seed density (Kruskal-Wallis test  $H = 36.15$ ;  $p < 0.01$ ), species richness ( $F_{7,72} = 9.85$ ,  $p < 0.01$ ) and Shannon's diversity ( $F_{7,72} = 5.73$ ,  $p < 0.01$ ) of soil seed banks also showed significant differences between vegetation patches (Fig. 3). Two vegetation patches, *Medicago* and *Genista*, represent the more extreme cases, with *Genista* patches having the highest values of vegetation cover, species richness and seed density. *Medicago* patches, on the contrary, had the lowest values.

#### 3.2. Rainfall simulations

We found significant differences in final infiltration rates ( $F_{6,14} = 3.70$ ,  $p = 0.02$ ; Fig. 4a), soil profile moistening rates ( $F_{6,14} = 9.71$ ,  $p < 0.01$ ; Fig. 4c) and sediment concentrations (Kruskal-Wallis test  $H = 17.01$ ,  $p < 0.01$ ; Fig. 4d) between vegetation patches. We observed similar differences between patches to those for vegetation traits, *Genista* and *Medicago* being the most different (Figs. 3 and 4).

#### 3.3. Soil moisture measurements

The repeated measures ANOVA applied to soil moisture data (see table 2) showed significant effects of patch, sensor depth and time. *Genista*, *Brachypodium*, *Lolium* and *Thymus* patches showed higher soil water content (Fig. 5). Regarding sensor depth, soil moisture generally increased with depth and, with respect to time, it was higher during spring and autumn. There was a significant interaction between vegetation

patch and sensor depth (table 2): soil water content in *Genista* patches increased with depth while *Brachypodium*, *Santolina* and *Medicago* patches showed constant values along the soil profile (Fig. 5). There was also a significant interaction between time and sensor depth, since differences in soil water content with depth became more patent during spring (Fig. 5). Detailed soil moisture dynamics of patches, interpolated along the soil profile during the study period, are shown in Appendix B.

At hillslope scale we observed significant differences in soil moisture between hillslopes at the three soil depths (Friedman ANOVA  $p < 0.001$ ). Hillslope 3 showed the highest soil moisture values while hillslope 1 the lowest (Fig. 5).

#### *3.4. Relationships between vegetation traits and soil hydrology*

Regarding plant species richness, we found significant correlations for final infiltration rate and soil moisture at 25 and 50 cm (Table 3). For vegetation cover, we found significant positive correlations with final infiltration rate and negative with runoff coefficient. With respect to soil seed bank species richness and diversity we found significant positive correlations with final infiltration rate and soil moisture at 25 cm.

#### *3.5. Soil properties*

We found significant differences in soil nutrients (N, P) and organic matter (Table 4), finding the highest and the lowest contents in *Genista* and *Medicago* patches respectively. There were also significant differences between patches in soil bulk density and soil surface strength, following the same trend as for soil nutrients. Maximum and minimum silt content values were found in *Medicago* and *Brachypodium* patches respectively (Table 4).

### 3.6. Seed germination

Germination experiments under controlled conditions highlighted a drastic effect of water potential on the germination rate of the different species (Appendix C). Parameters  $P_0$  (threshold water potential level for seed germination),  $G_{max}$  (maximum germination rate) and the  $R^2$  of the fitted sigmoid equation, together with threshold soil moisture values are shown in table 5. In general, herbaceous species had lower moisture requirements (i.e. more negative  $P_0$  water potential values) for germination when compared to woody species (*G. scorpius*, *T. vulgaris*, *S. chamaecyparissus*), except for *M. sativa*, which was introduced during revegetation practices. The non parametric bifactorial ANOVA applied to the germination suitability index showed significant effects of vegetation patch ( $F_{7,192}=13.64$ ,  $p<0.001$ ) and species ( $F_{7,192}= 6.99$ ,  $p<0.001$ ). Two species showed fewer suitable days for germination (*Genista scorpius* and *Brachypodium retusum*). With regards to vegetation patches, *Brachypodium*, *Medicago* and *Genista* patches appeared to be potentially more suitable microsites for germination, contrasting with *Santolina* patches, which presents less suitable soil moisture values for germination (Fig. 6).

The germination suitability index was significantly different between hillslopes (Friedman ANOVA  $p<0.001$ , Fig. 6). Therefore, conditions in hillslope 1 were less suitable for germination than in the other hillslopes.

## 4. Discussion

Descriptors of the vegetation-hydrology interactions have been explored under the TTRP framework (Ludwig et al., 2005) described above in four steps: a) soil water availability for plants in different vegetation patches; b) ecological performance of vegetation patches related to soil water content; c) feedback effects of vegetation on soil water availability, specifically by the enhance of soil water infiltration; and d) the effects of volume of overland flow routing through the hillslope on eco-hydrological interactions.

### 4.1. Soil moisture availability in vegetation patches

Measured soil moisture values should be interpreted as a result of the balance between water inputs through infiltration and water used by plants, which lead to, for example, higher water stress at the end of the drought period in patches with higher vegetation cover. Therefore, the interpretation of soil moisture results should be made together with plant cover values. The three vegetation patches that act as sinks, *Lolium*, *Brachypodium* and *Genista*, incorporated higher water volumes in depth which were consumed by vegetation, depleting soil moisture at the end of the growth season (Fig. 5, Appendix B). Soil water content in these sink patches is the result of higher rainfall infiltration capacity on site and/or the obstruction of overland flow generated in upslope source patches. In the case of *Genista* patches, vegetation clumps are especially efficient at both infiltrating water onsite and obstructing the water flow coming from the upper part of the hillslope, thus modifying micro-environmental conditions through the concentration of soil moisture. In general, these results agree with different studies on the effects of vegetation on soil water content compared to bare open areas (Eldridge and Freudenberger, 2005; Joffre and Rambal, 1993; Shumway, 2000). Previous studies showed that the proliferation of *Lolium* and *Brachypodium* patches in these hillslopes

was associated to the generation of depositional micro-topographic structures (i.e. rill fans or splays) that act as geomorphologically-driven "surface sinks" of fine-grained sediments and nutrients with favourable conditions for the growth of perennial grasses. These structures are generated by differential erosion in the early stages of succession after hillslope construction, suggesting a key role of overland flow in structuring vegetation (Merino-Martin et al., 2012). This spatial arrangement of species and soil moisture content is also consistent with observations on other ecosystems with banded vegetation patterns and suggest a coupling between source-patches up-slope and downslope sinks (Seghieri and Galle, 1999; Seghieri et al., 1997). This coupling has been further confirmed in an runoff-exclusion experiment study developed on the three sink patches (Espigares et al., 2012).

#### *4.2. Ecological performance of vegetation patches associated to soil water availability*

Sink patches (*Genista*, *Brachypodium*, *Lolium*) showed higher species richness and diversity compared with other patches located on the same hillslope (Fig. 3). We didn't find this pattern for soil seed bank density, where *Brachypodium* patches had a particularly low seed bank density. This could be explained by the resprouting strategy of *B. retusum*, advantageous over seeding for this rhizomatous perennial grass, that allows the species to persist continuously after disturbance (Bond and Midgley, 2001).

The analysis of the implications of surface soil moisture for germination showed that the different vegetation patches reached different suitable days for germination, with two sink patches (*Genista* and *Brachypodium*) and one source patch (*Medicago*) being the best micro-environments for germination (Fig. 6). However, our findings highlight final infiltration rate and soil moisture in depth as the variables that best correlate with vegetation traits, in contrast with soil surface moisture, which was not

correlated with the ecological descriptors of patch structure (table 3). Surface soil moisture (first 5 cm of the soil) is likely to strongly fluctuate with time due to direct evaporation, and therefore periodical sampling may not record significant changes among treatments at this soil depth. Our results suggests that soil moisture in depth (at 25 and 50 cm) is ecologically more significant (i.e. it has broader implications on community richness and diversity) than surface soil moisture. In fact, although surface soil moisture heterogeneity has implications for colonization (e.g. germination), our results indicate that soil moisture in depth was more significant for structuring vegetation patches, probably controlling further vegetation establishment and plant survival.

Plant community composition depends to a large extent on the amount and spatial distribution of soil moisture available for plants (Breshears and Barnes, 1999). Our results showed how ecohydrological heterogeneity can influence plant germination and colonization processes by driving the spatial distribution of soil moisture on hillslopes. Our study was not designed to measure growth pulses in *Genista* patches (as would be expected under the TTRP conceptual framework), however we have found a pulse of floristic and soil seed bank richness in the understorey plant community. Similar results have been also found in a recent research on coal mine sites (Alday et al., 2014), where natural shrub encroachment was identified as a key process driving the generation of spatial heterogeneity in micro-environmental conditions, hence inducing greater overall plant diversity.

#### 4.3. Feedback effect of vegetation on soil water availability through an increase in water infiltration

A third type of vegetation-hydrology interaction, that drives the performance of our reclaimed semiarid vegetation communities, deals with the feedback effect of vegetation on soil water availability. Results from rainfall simulation experiments and soil properties analyses show that infiltration capacity and soil macroporosity (as opposed to bulk density) are higher in sink-patches (*Genista*, *Lolium* and *Brachypodium*) than in source patches (*Thymus*, *Santolina*, *Dactylis* and *Medicago*). Furthermore, *Genista* patches were the most favourable microsites for water infiltration and storage. Again, these differences can be attributed to the patch structuring effects of both differential erosion (i.e. the generation of rill fans or splays) and vegetation in the case of *Lolium* and *Brachypodium* patches, but only to the effect of vegetation in the case of *Genista* patches (Merino-Martin et al., 2012).

In general, soil enhancement by woody legumes (e.g. *Genista scorpius*) has been shown to have positive effects on neighbours in nutrient-poor environments (Shumway, 2000), and particularly in Mediterranean systems (Aguilera et al., 1999; Moro et al., 1997). Gomez Aparicio et al. (2005) in a study about shrub facilitation found that below-ground, shrubs did not modify soil physical characteristics, organic matter, total N and P, or soil moisture, but significantly increased available K. Conversely, in our study we found differences in N, P, organic matter and soil physical properties (i.e. bulk density and surface crusting) between the different vegetation patches, with sinks showing a higher content in nutrients and lower bulk density and soil surface strength. The fact that our system is a restored ecosystem under succession may explain the large impact of vegetation on enhancing soil properties and conditions. In this regard, the use of shrubs (Castro et al., 2002; Gomez-Aparicio et al., 2004; Padilla and Pugnaire, 2006)



and perennial grasses (*Stipa sp.*, Gasque and García-Fayos, 2004) for restoration has been widely applied for Mediterranean and semiarid areas.

Overall, our results allow us to consider the impact of *Genista* patch as a vegetation-mediated ecohydrological feedback or “plant nucleation” process (Puigdefábregas et al., 1999) that enhances microsite ecological and hydrological attributes for water collection and vegetation establishment. Our findings agree with those by Maestre et al. (2009), who found that shrubs can reverse land degradation and desertification in drylands; in our case, promote vegetation recovery along vegetation succession. They discuss how shrubs with canopies that spread horizontally (as this is the case for *G. scorpius* in our study) enhance the sink behaviour of the vegetation patch, contrasting with shrubs that usually colonize other semiarid areas of North America (e.g. mesquite, creosotebush) and generally are associated with land degradation and the acceleration of soil erosion processes (Wainwright et al., 2000). Rango et al. (2006) called these sink patches “islands of enhanced hydrologic activity” in the Chihuahuan Desert. Other authors refer to them as “fertility islands” (Barthes and Roose, 2002; Cammeraat and Imeson, 1998; Cerdà, 1998; Puigdefábregas et al., 1999) . The use of shrubs as ecosystem engineers to enhance overall environmental heterogeneity and different plant communities in restoration has been recently suggested (Alday et al., 2014). However, these authors emphasize that the effectiveness of these ecosystem engineers should be tested in future research.

#### *4.4. The modulation of ecohydrological interactions by overland flow volume.*

Soil moisture content at the hillslope scale was negatively related to the amount of overland flow (Fig. 5), showing higher soil moisture contents at the three soil depths whenever runoff volume decreased. The effects of erosion processes accentuating

drought stress and decreasing productivity have been largely described in intensively eroded arid and semiarid areas (Espigares et al., 2011; Lal, 1998; Pimentel and Harvey, 1999). Our study suggests that in reclaimed hillslopes where erosion rates are not particularly high (rill erosion rates in the experimental slopes are  $<10 \text{ t ha}^{-1} \text{ yr}^{-1}$ , Appendix A), the formation and downslope routing of overland flow is one of the main factors decreasing soil moisture at the hillslope scale. We also found that hillslope runoff decreased soil water content at the patch scale, as evidenced by soil moisture differences in *Santolina* patches between hillslopes 1 and 3, with significantly lower water contents in the hillslope with the highest runoff volumes. This suggests that if the sink capacity of a surface patch (i.e. the capacity of the patch to obstruct and infiltrate water runoff) is exceeded, the spatial connectivity of overland flow increases at larger scales, leading to the loss of runoff away from the hillslope and therefore decreasing in-slope soil water content, as observed for the case of hillslope 1. Similarly, other applications of the TTRP model in natural arid and semiarid environments indicate that soil-water-vegetation feedbacks driven by coupled reductions (or increases) in sink capacity of surface patches at small scales with broad-scale amplification (or reduction) of the spatial connection of overland flow have a critical role for the activation/promotion of land degradation (or restoration) processes (Moreno-de las Heras et al., 2012; Okin et al., 2009; Tongway and Ludwig, 1996).

Overland flow also influences the germination opportunities for plants at the hillslope scale, decreasing germination probabilities as hillslope overland flow increases (Fig. 6). Traditionally, plant colonisation has been considered as limited by the distance between appropriate seed source areas and target areas in humid reclaimed environments (Kirmer and Mahn, 2001; Novak and Prach, 2003). Bochet *et al.* (2007) and Tormo *et al.* (2006), identified water availability as the main factor controlling

germination processes in semiarid roadslopes. According to these results, we suggest that in reclaimed semiarid environments, where water is the main limiting factor for vegetation growth, overland flow is one of the main factors driving plant colonization by increasing water deficit in the soil, not only for germination at the surface (5 cm depth), but also in depth (at 25 and 50 cm) for further plant establishment and plant community development.

#### *4.5. Practical implications.*

Similar ecohydrological interactions have been well described for semiarid ecosystems spatially structured in mosaics of coupled runoff sources and sinks resulting from feedbacks in a dynamic equilibrium (Valentin et al., 1999). Imeson and Prinsen (2004) stated that the spatial differentiation between sources and sinks of surface resources is a dynamic property of many semiarid ecosystems and it feeds back to plant growth as well as bare patch development. In our case, we cannot anticipate whether our system is in a dynamic equilibrium through time or whether we are studying a temporary stage of succession with a tendency to be fully covered by vegetation. However, management of spatial heterogeneity (i.e. promotion of patch formation and manipulation of the spatial coupling or connection between source patches and sinks with optimum conditions for vegetation establishment) may prove useful for stabilizing these novel systems, especially at the early stages when vegetation density is low and soil surface process (e.g. surface crusting, runoff generation, soil erosion and sedimentation) are particularly active (Hancock and Willgoose, 2004, Tormo et al. 2006, Moreno-de las Heras et al. 2009, Alday et al. 2014).

Two patch-forming ecohydrological interrelationships (or feedbacks) were found in this study: a patch-forming feedback where surface hydrology (i.e. local

sedimentation and runoff infiltration in rill fans or splays) is the main driver for vegetation establishment (in hillslopes 1 and 2, where grasses play a passive role on patch dynamics), and a biologically-driven feedback where vegetation (*Genista scorpius* shrubs, in hillslope 3) is the main driver of local surface hydrology and patch dynamics. This scheme follows the approach by Puigdefábregas et al. (1999), who explained these two types of mosaic generating process: (1) mosaics driven by differential erosion, where plant cover plays a passive role on structuring patch dynamics, and (2) mosaics resulting from “plant nucleation” processes where vegetation plays an active role. As overland flow and its ecological impacts are determined by hillslope topography design and topsoil selection, reclamation practices must be appropriately managed in order to develop a functional ecosystem. Rango et al. (2006) proposed that in order to rehabilitate degraded landscapes, it may be appropriate to mimic the patchy nature of fully functional arid and semiarid ecosystems, diverting water to target areas for the establishment of vegetation. In that respect, the presence of local sedimentation microsites (e.g. surface depressions, rill discontinuities, surface splays) offer important advantages for the promotion of patch dynamics and early development of vegetation. The use of keystone plant species with a high capacity to modify microsite conditions and obstruct the surface flow of water runoff and sediments (such as *Genista scorpius* in this study) can also help to enhance the development and dynamics of vegetation and to control soil erosion processes in these semiarid reclaimed landscapes.

## **5. Conclusions**

Our results from semiarid reclaimed hillslopes were consistent with the TTRP conceptual model (Ludwig et al., 2005). Vegetation patches showed diverse hydrological behaviours and soil moisture contents, acting as runoff sources or sinks. The hydrological behaviour of three sink vegetation patches (*Lolium*, *Brachypodium*

and *Genista*) was due to a higher rainfall infiltration capacity on site and/or the obstruction of overland flow generated in upslope source patches. Furthermore, there were important ecological consequences derived from the heterogeneous spatial distribution of soil moisture. Sink patches showed higher species richness and diversity, higher infiltration capacity and soil macroporosity. Remarkably, *Genista* sink patch enhanced microsite ecological and hydrological attributes for water collection and vegetation establishment. Overall, overland flow influenced germination opportunities for plants at the patch and hillslope scales, decreasing germination probabilities as hillslope overland flow increased. Our results highlight the significance of overland flow as it modifies soil moisture distribution and hence, influences vegetation dynamics and ecological succession even at moderate runoff rates ( $<10 \text{ t ha}^{-1} \text{ yr}^{-1}$ ).

The TTRP general framework was previously applied in natural semiarid ecosystems in dynamic equilibrium throughout the world. In this study we have also corroborated this conceptual framework for a highly dynamic and unstable restored ecosystem subjected to ecological succession.

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**Figure captions:**

**Figure 1.** The Trigger–Transfer–Reserve–Pulse (TTRP) framework linking temporal (trigger) events, such as rainstorm inputs of water, through spatial transfer (runoff–runon) and reserve (patch) processes, to pulse events, such as plant growth. These linkages are denoted with solid arrows. Feedbacks and flows out of the system are indicated with dashed or dotted arrows (taken from Ludwig *et al.* 2005).

**Figure 2.** a) Selected slopes; the red line shows the upslope structure that generates extra-overland flow. b) abundance and spatial distribution of the different vegetation patches in the three slopes. G: *Genista*; B: *Brachypodium* L: *Lolium*; T: *Thymus*; D: *Dactylis*; S: *Santolina* (hillslope 1); M: *Medicago*.

**Figure 3.** Floristic traits of the different vegetation patches. a) Plant species richness; b) Seed density of soil seed bank; c) Species richness of soil seed bank; d) Shannon's diversity of soil seed bank. G: *Genista*; B: *Brachypodium* L: *Lolium*; T: *Thymus*; D: *Dactylis*; S1: *Santolina* in hillslope 1; S3: *Santolina* in hillslope 3; M: *Medicago*. Different letters indicate significant differences ( $p < 0.01$ )

**Figure 4.** Soil hydrological properties of the different vegetation patches. a) Final infiltration rate ( $\text{mm h}^{-1}$ ); b) runoff coefficient (%); c) soil profile moistening rate ( $\text{cm h}^{-1}$ ); d) sediment concentration ( $\text{g l}^{-1}$ ). G: *Genista*; B: *Brachypodium* L: *Lolium*; T: *Thymus*; D: *Dactylis*; S: *Santolina* (hillslope 1); M: *Medicago*.

**Figure 5.** 2007–08 soil moisture dynamics in vegetation patches and hillslopes at three soil depths. b) 5cm; c) 25cm; d) 50 cm. G: *Genista*; B: *Brachypodium* L: *Lolium*; T: *Thymus*; D: *Dactylis*; S1: *Santolina* in hillslope 1; S3: *Santolina* in hillslope 3; M: *Medicago*. Figure 4a shows meteorological data (daily precipitation and daily mean air temperature) throughout the monitored period.

**Figure 6.** Germination suitability index (a) for each vegetation patch (b) for each hillslope. G: *Genista*; B: *Brachypodium* L: *Lolium*; T: *Thymus*; D: *Dactylis*; S1: *Santolina* (hillslope 1); M: *Medicago*.

**Appendix A.** Descriptive features for the three experimental slopes (mean  $\pm$  SE) (modified from Merino-Martin *et al.*, 2012)

**Appendix B.** 2007–08 soil moisture dynamics in the vegetation patches along depth.

**Appendix C.** Seed germination rates of each species under different water potentials.



**Table 1.** Characteristic species and mean vegetation cover ( $\pm$  SE) of the seven vegetation patches.

Vegetation community	Indicator species	Vegetation cover (%)	
<i>Genista</i>	<i>Genista scorpius</i> , <i>Anacyclus clavatus</i> , <i>Bromus rubens</i> , <i>Cerastium pumilum</i> , <i>Eryngium campestre</i> , <i>Plantago lanceolata</i> , <i>Sanguisorba minor</i> , <i>Xeranthemum inapertum</i>	81.3 $\pm$ 12.5	a
<i>Brachypodium</i>	<i>Brachypodium retusum</i> , <i>Avena sterilis</i> , <i>Avenula bromoides</i> , <i>Barkhausia haenseleri</i> , <i>Festuca sp.</i> , <i>Koeleria vallesiana</i>	93.7 $\pm$ 3.6	a
<i>Lolium</i>	<i>Lolium perenne</i>	67.3 $\pm$ 11.1	a
<i>Thymus</i>	<i>Thymus vulgaris</i> , <i>Desmazeria rigida</i>	23.3 $\pm$ 3.6	ab
<i>Dactylis</i>	<i>Dactylis glomerata</i>	17.3 $\pm$ 1.7	ab
<i>Santolina</i>	<i>Santolina chamaecyparissus</i>	19.3 $\pm$ 6.1	ab
<i>Medicago</i>	<i>Medicago sativa</i> , <i>Scorzonera laciniata</i>	2.7 $\pm$ 0.4	b








**Table 2.** Results of the repeated measures ANOVA applied to soil water content in vegetation patches.

Effect	Degr. of freedom	F	p
Vegetation patch	7	14.811	<0.000001
Sensor depth	2	13.012	0.000031
Vegetation patch*Sensor depth	14	3.390	0.000795
Time	16	546.762	<0.000001
Time*Vegetation patch	112	6.896	<0.000001
Time*Sensor depth	32	18.608	<0.000001
Time*Vegetation patch*Sensor depth	224	2.482	<0.000001

**Table 3.** Results of pearson correlations between hydrological and vegetation properties in vegetation patches. If: final infiltration rate; Qc: Runoff coefficient; Sm: Soil moisture. (\*\*:  $p < 0.01$ , \*:  $p < 0.05$ ; n.s.: no significant).

Cover type features		If	Qc	Sm 5cm	Sm 25cm	Sm 50cm
Species richness (vegetation)	p	0.012	0.059	0.316	0.032	0.031
	R	+0.864	-0.752	+0.446	+0.797	+0.802
		*	n.s.	n.s.	*	*
Vegetation cover	p	0.006	0.027	0.450	0.1087	0.052
	R	+0.899	-0.811	+0.339	+0.657	+0.750
		**	*	n.s.	n.s.	n.s.
Species richness (seed bank)	p	0.048	0.132	0.555	0.009	0.088
	R	+0.759	-0.627	+0.272	+0.880	+0.687
		*	n.s.	n.s.	**	n.s.
Shannon's diversity (seed bank)	p	0.032	0.155	0.452	0.003	0.069
	R	+0.796	-0.599	+0.434	+0.919	+0.719
		*	n.s.	n.s.	**	n.s.
Soil seed bank density	p	0.529	0.709	0.669	0.068	0.557
	R	+0.288	-0.173	+0.2	+0.719	+0.270
		n.s.	n.s.	n.s.	n.s.	n.s.

**Table 4.** Edaphic properties of vegetation patches. Abbreviations: EC: Electrical conductivity; w/v: relation weigh (soil)/volume (water):1/2; AWHC: Available water holding capacity. <sup>1</sup> Measured in three composite samples (each formed by three subsamples) in each vegetation patch or runoff contributing area from the first 10 cm. <sup>2</sup> Measured in 15 unaltered soil cores (3cm height by 5 cm diameter); 3 randomly distributed soil cores for each 7 vegetation patch. <sup>3</sup> Measured in 15 randomly distributed samples in the different vegetation patches during four campaigns (seasonal measurements). Values with "\*" differ significantly at  $\alpha = 0.05$ . Values with "\*\*\*" differ significantly at  $\alpha = 0.01$ . <sup>1</sup> Tested using Kruskal-Wallis and Mann-Whitney U tests. <sup>2</sup> Tested using ANOVA and Tukey's *post hoc* tests. <sup>3</sup> Tested using Friedman test and Wilcoxon-Nemenyi-McDonald-Thompson *post-hoc* tests.

	<i>Genista</i>	<i>Braquipedium</i>	<i>Lolium</i>	<i>Thymus</i>	<i>Dactylis</i>	<i>Santolina</i>	<i>Medicago</i>	p
								
<b>pH<sup>1</sup></b>	8.2±0.1 a	8.4±0.1 a	8.2±0.1 a	8.3±0.1 a	8.5±0.1 a	8.5±0.1 a	7.9±0.2 a	n.s.
<b>EC<sup>1</sup> (dSm<sup>-1</sup>)</b>	0.07±0.01 a	0.08±0.02 a	0.04±0.01 a	0.05±0.01 a	0.05±0.01 a	0.05±0.01 a	0.07±0.01 a	n.s.
<b>Carbonates<sup>1</sup> (%)</b>	8.0±0.8 ab	9.4±0.7 ab	10.1±0.4 ab	11.6±0.6 a	9.7±1.1 ab	9.5±1.1 ab	1.9±0.5 b	*
<b>Nitrogen<sup>1</sup> (%)</b>	0.18±0.04 a	0.12±0.01 ab	0.09±0.01 ab	0.09±0.01 ab	0.06±0.01 ab	0.06±0.01 ab	0.03±0.01 b	**
<b>Organic matter<sup>1</sup> (%)</b>	4.4±0.9 a	2.8±0.3 ab	2.1±0.2 ab	2.3±0.5 ab	1.6±0.2 ab	0.5±0.3 ab	0.3±0.1 b	**
<b>C/N<sup>1</sup></b>	13.9±1.7 a	13.8±0.3 a	14.1±0.7 a	15.3±2.9 a	15.8±0.8 a	5.8±2.9 a	6.9±1.8 a	*
<b>Phosphorus<sup>1</sup> (%)</b>	13.7±3.3 a	11.7±1.3 a	5.7±0.3 ab	3.7±0.3 ab	2.7±0.3 b	4.3±0.3 ab	4.3±0.3 ab	**
<b>Clay<sup>1</sup> (%)</b>	19.3±0.3 a	19.7±0.9 a	12.3±0.9 a	18.0±0.6 a	17.3±0.3 a	20.0±1.0 a	15.0±1.2 a	*
<b>Silt<sup>1</sup> (%)</b>	29.0±1.0 ab	25.7±3.2 a	38.3±6.1 ab	38.3±1.8 ab	43.0±2.0 ab	46.3±0.7 ab	52.7±0.9 b	*
<b>Sand<sup>1</sup> (%)</b>	51.7±1.2 a	51.3±3.9 a	49.3±6.6 a	43.7±1.2 a	39.7±2.3 a	33.7±0.3 a	32.3±2.0 a	*
<b>AWC<sup>1</sup> (%)</b>	6.4±0.3 a	8.5±0.3 a	8.1±1.4 a	6.9±0.1 a	9.0±0.4 a	8.8±0.2 a	9.1±0.7 a	n.s.
<b>Bulk density<sup>2</sup> (Mg m<sup>-3</sup>)</b>	1.13±0.04 a	1.30±0.05 b	1.41±0.04 b	1.55±0.02 cd	1.41±0.03 bc	1.42±0.02 bc	1.61±0.01 d	**
<b>Soil surface strength<sup>3</sup> (kg)<sup>3</sup></b>	2.2±2.1 a	4.7±3.8 ab	4.5±4.0 ab	4.7±3.7 ab	4.8±3.9 ab	4.4±3.2 ab	5.4±3.4 b	*

**Table 5.** Coefficients of the seed-germination sigmoid function (eq. 2) and corresponding water content (%) at threshold  $P_0$  for different species.  $P_0$ : water potential threshold value for seed germination;  $G_{max}$ : maximum germination rate.

Species	$P_0$ (MPa)	$G_{max}$ (%)	$R^2$	Soil moisture (%)
<i>Genista scorpius</i>	-0.611	46.26	0.737	$12.36 \pm 2.47$
<i>Brachypodium retusum</i>	-0.724	49.09	0.745	$12.04 \pm 2.46$
<i>Lolium perenne</i>	-0.766	72.11	0.955	$11.94 \pm 2.46$
<i>Thymus vulgaris</i>	-0.569	78.43	0.928	$12.50 \pm 2.47$
<i>Dactylis glomerata</i>	-0.741	89.19	0.948	$11.99 \pm 2.46$
<i>Santolina chamaecyparissus</i>	-0.620	81.20	0.874	$12.34 \pm 2.47$
<i>Medicago sativa</i> *	-0.416	88.93	0.970	$13.13 \pm 2.48$
<i>Aegilops geniculata</i>	-1.161	79.33	0.796	$11.19 \pm 2.45$

\* Data taken from Moreno-de las Heras and collaborators (2011)

881 **Appendix A.**

	N	Hillslope 1	Hillslope 2	Hillslope 3
Date of reclamation		1988	1988	1987
<i>Topography</i>				
Hillslope area (m <sup>2</sup> )		497.5	510.6	1474.3
Hillslope gradient (°)		20	20	20
Water-Contributing Area (m <sup>2</sup> )		50.4	22.7	0
Aspect		North	North	North
<i><sup>1</sup>Soil traits</i>				
Stoniness (%)	9	39.2 ± 4.5	a 40.5 ± 3.2	a 41.9 ± 3.4
Sand (%)	9	44.8 ± 2.6	a 45.6 ± 2.7	a 44.0 ± 3.0
Silt (%)	9	28.7 ± 0.3	a 25.2 ± 1.1	a 29.8 ± 1.2
Clay (%)	9	26.6 ± 2.4	a 29.3 ± 1.6	a 26.3 ± 1.8
Texture	9	Clay loam	Clay loam	Clay loam
pH -H <sub>2</sub> O; w/v: 1/2-	9	8.4 ± 0.3	a 8.3 ± 0.2	a 8.01 ± 0.2
EC -w/v: 1/2- (dS m <sup>-1</sup> )	9	0.3 ± 0.1	a 0.3 ± 0.01	a 0.7 ± 0.4
Organic matter (%)	9	1.2 ± 0.3	a 1.6 ± 0.34	a 2.0 ± 0.4
CaCO <sub>3</sub> (%)	9	7.3 ± 0.4	a 6.2 ± 0.38	a 6.8 ± 0.3
<sup>2</sup> Bulk density (Mg m <sup>-3</sup> )	27	1.5 ± 0.1	a 1.5 ± 0.03	a 1.4 ± 0.01
<i><sup>3</sup>Cover features</i>				
Bare soil cover (%)	105	44.6 ± 3.1	a 32.3 ± 3.9	b 23.7 ± 2.8
Stone cover (%)	105	25.5 ± 3.0	a 22.7 ± 1.6	a 21.1 ± 2.6
	105	5.4 ± 1.8	a 1.1 ± 0.4	b 4.0 ± 1.9
Litter cover (%)				b
Plant cover (%)	105	24.4 ± 2.8	a 43.9 ± 4.1	b 51.2 ± 4.2
<i><sup>3</sup>Plant traits</i>				
Species Richness	105	3.83 ± 0.28	a 6.43 ± 0.44	b 9.26 ± 0.55
Shannon's index	105	0.80 ± 0.08	a 1.21 ± 0.08	b 1.30 ± 0.08
<i>Erosion features</i>				
<sup>4</sup> Sheet Erosion Index	9	0.70 ± 0.09	a 0.59 ± 0.05	a 0.52 ± 0.06
<sup>5</sup> Rill density (m m <sup>-2</sup> )	3	0.58	0.00	0.00
<sup>6</sup> Rill erosion rate <sup>4</sup> (t ha <sup>-1</sup> yr <sup>-1</sup> )	3	8.41	0.00	0.00
<sup>7</sup> Runoff coefficient (%)	3	15.9 ± 3.0	a 2.2 ± 0.5	b 0.33 ± 0.17
<sup>7</sup> Sediment yield (g/m <sup>2</sup> )	3	107.3 ± 36.0	a 4.8 ± 1.8	b 0.23 ± 0.07

882  
883 Abbreviations: N: Number of samples; EC: Electrical conductivity; w/v: relation weight (soil) / volume  
884 (water).

885 <sup>1</sup>Measured in three composite samples (each formed by three subsamples) from the first 10 cm in three  
886 transects regularly distributed along the hillslope during winter 2005.

887 <sup>2</sup>Measured in nine randomly distributed unaltered soil cores (3cm height by 5 cm diameter).

888 <sup>3</sup>Cover, visually estimated in 35 regularly distributed 0,25 m<sup>2</sup> plots per hillslope during spring 2006.

889 <sup>4</sup>Measured by the relationship: stone cover/stoniness; following Moreno-del Heras et al. (2008).

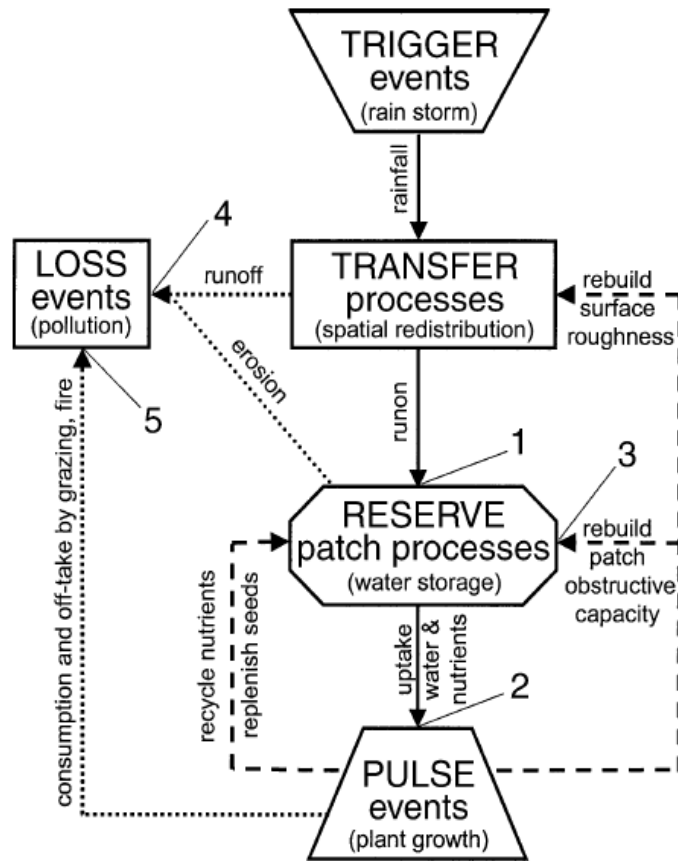
890 <sup>5</sup>Linear rill length (m) measured per surface area (m<sup>2</sup>).

891 <sup>6</sup>Measured from rill network dimensions following Morgan (1997).

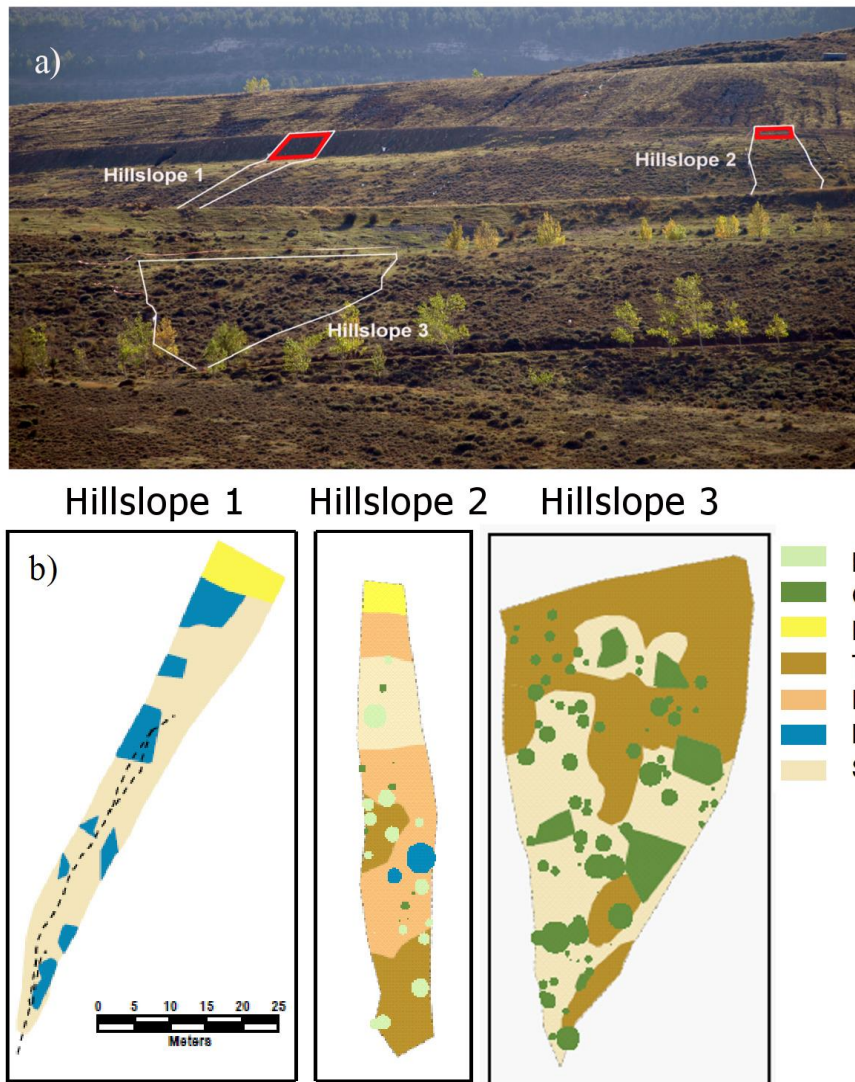
892 <sup>7</sup>Runoff and sediment yield monitored on the three experimental slopes from October 2007 to December  
893 2008 (Merino-Martín et al., 2012).

894  
895 All physico-chemical soil characteristics were analyzed following standardized methods proposed by the  
896 Spanish Ministry of Agriculture (MAPA, 1994). Values with the same letters (a-c) within rows do not  
897 differ significantly at  $\alpha=0,05$ . Tested using Kruskal-Wallis and Mann-Whitney post-hoc tests.

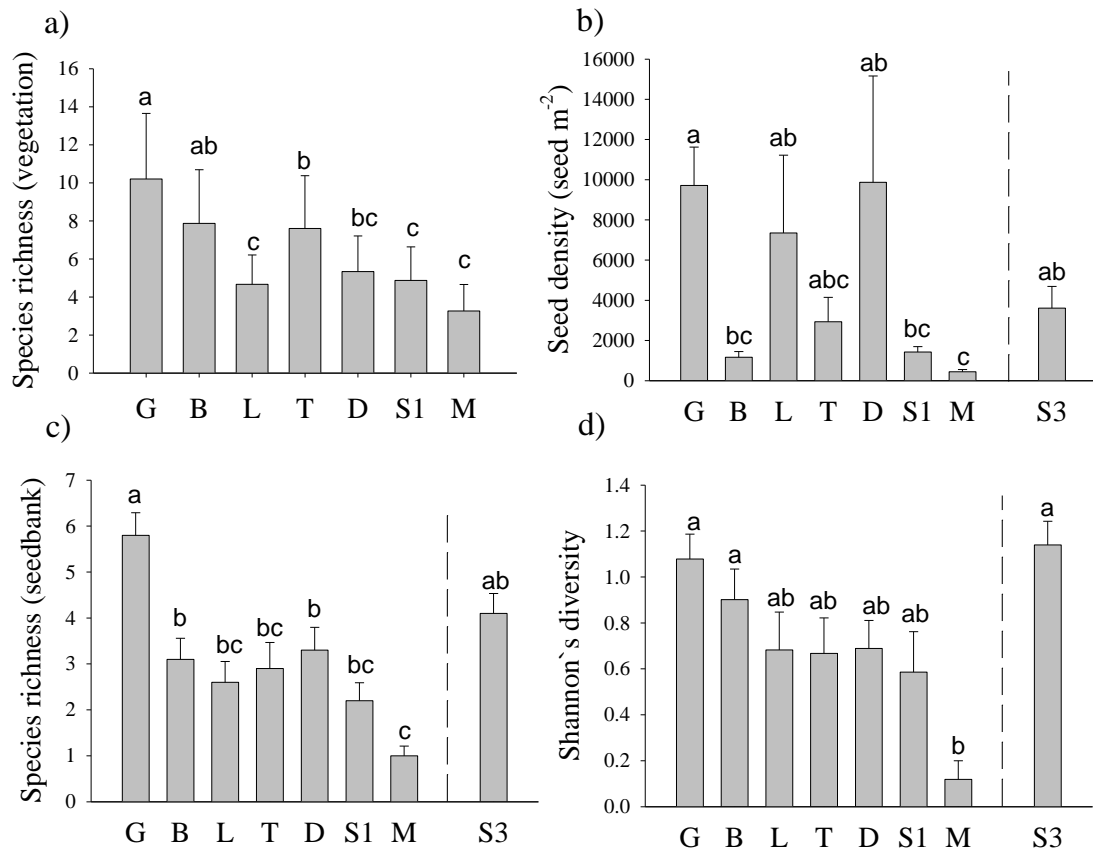
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**Figure 1**

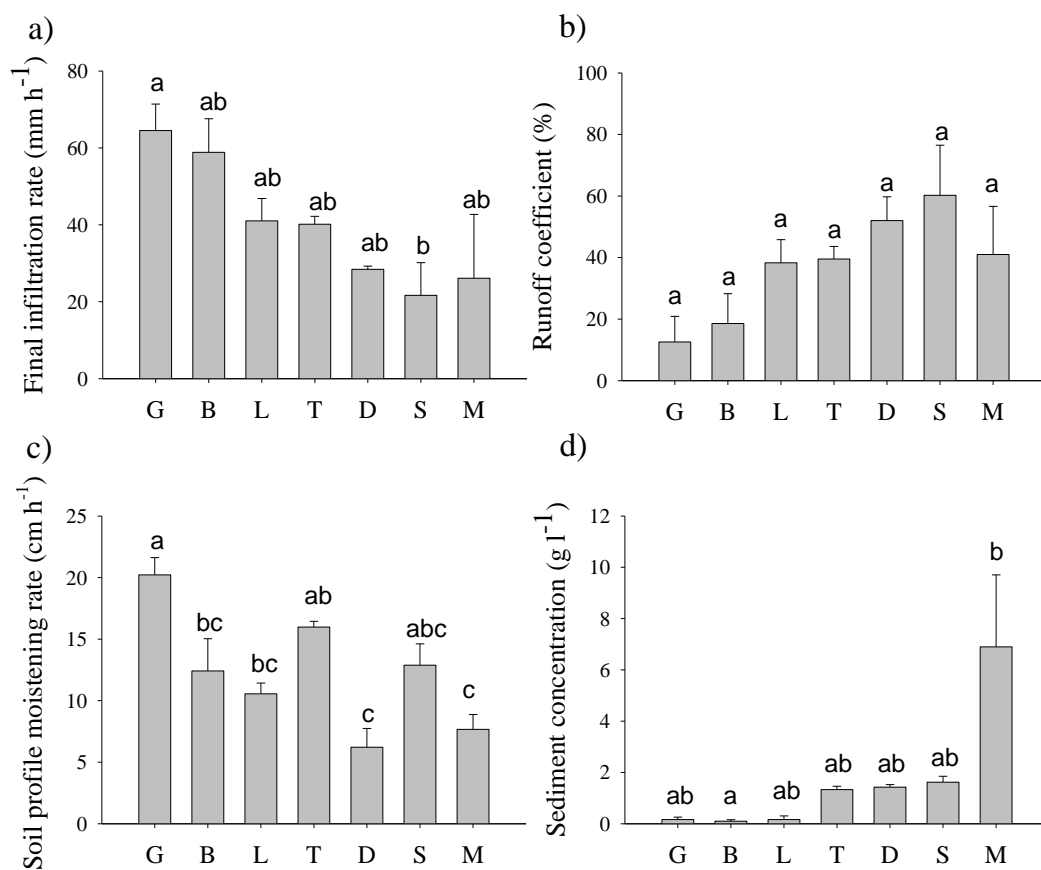


**Figure 2**

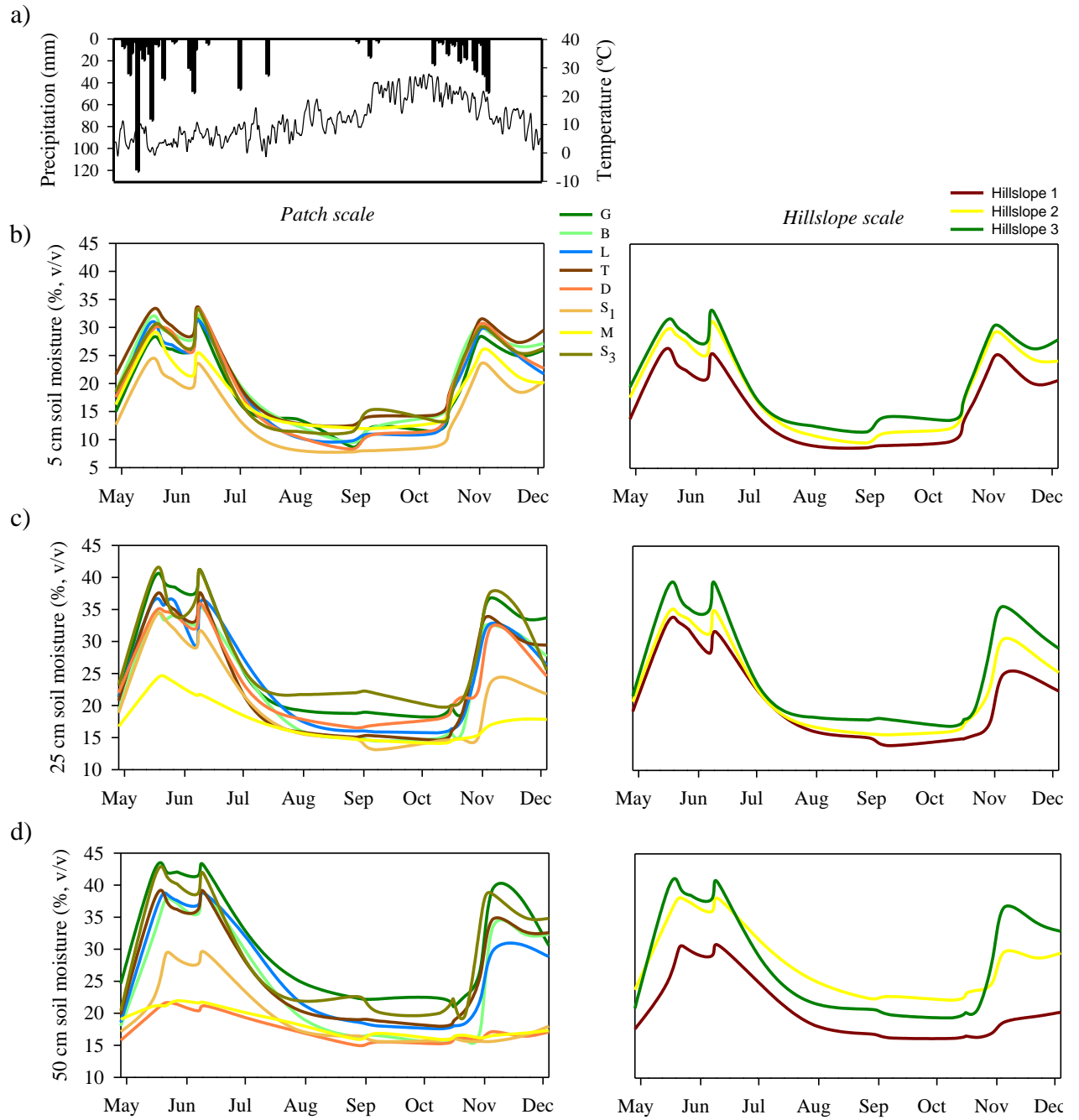


**Figure 3**

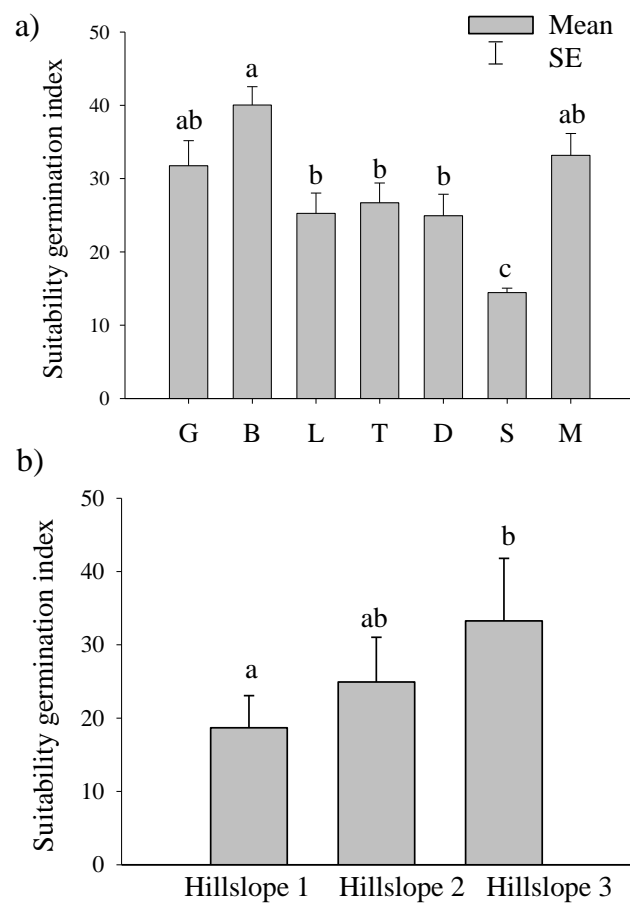




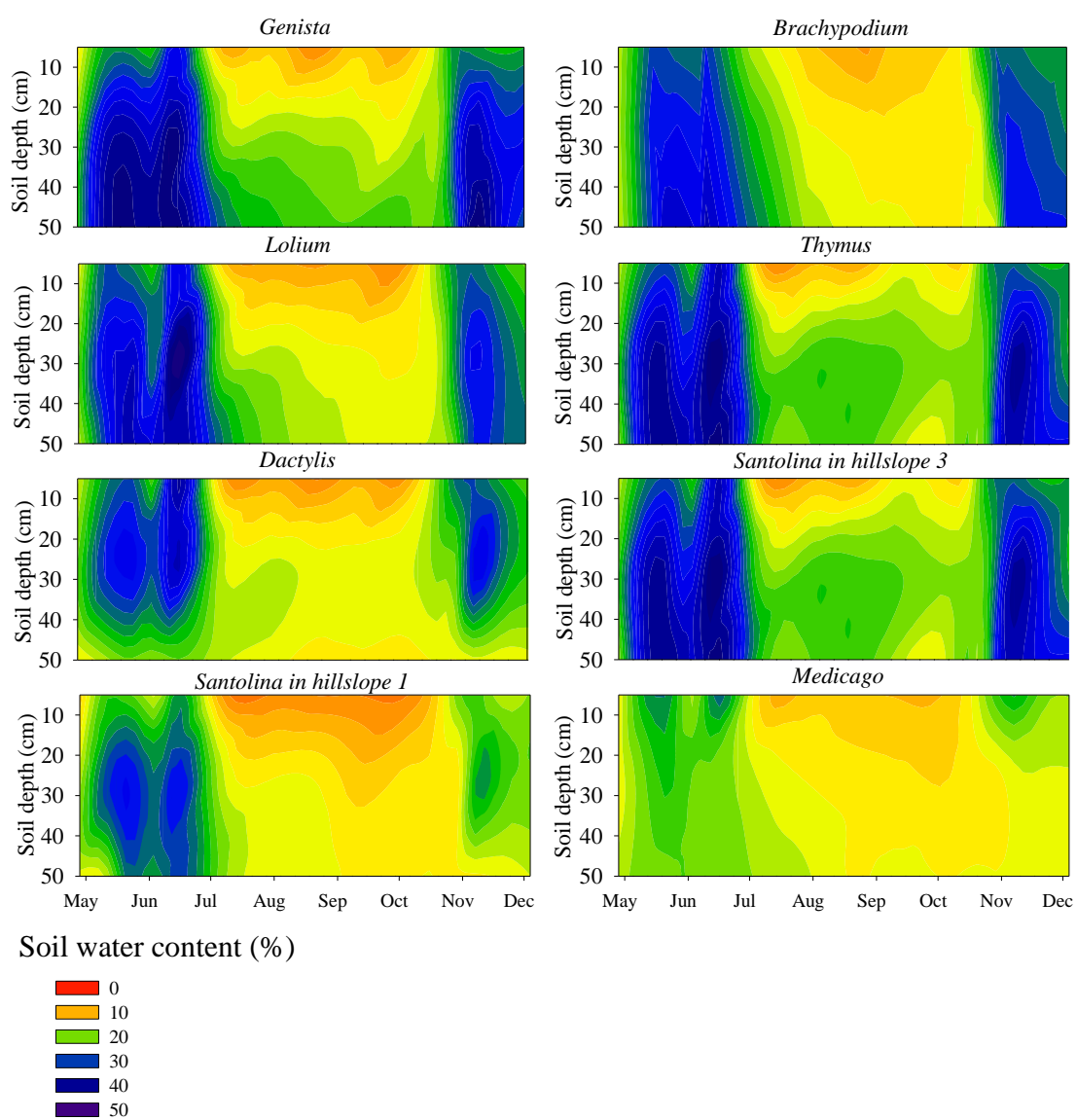
**Figure 4**



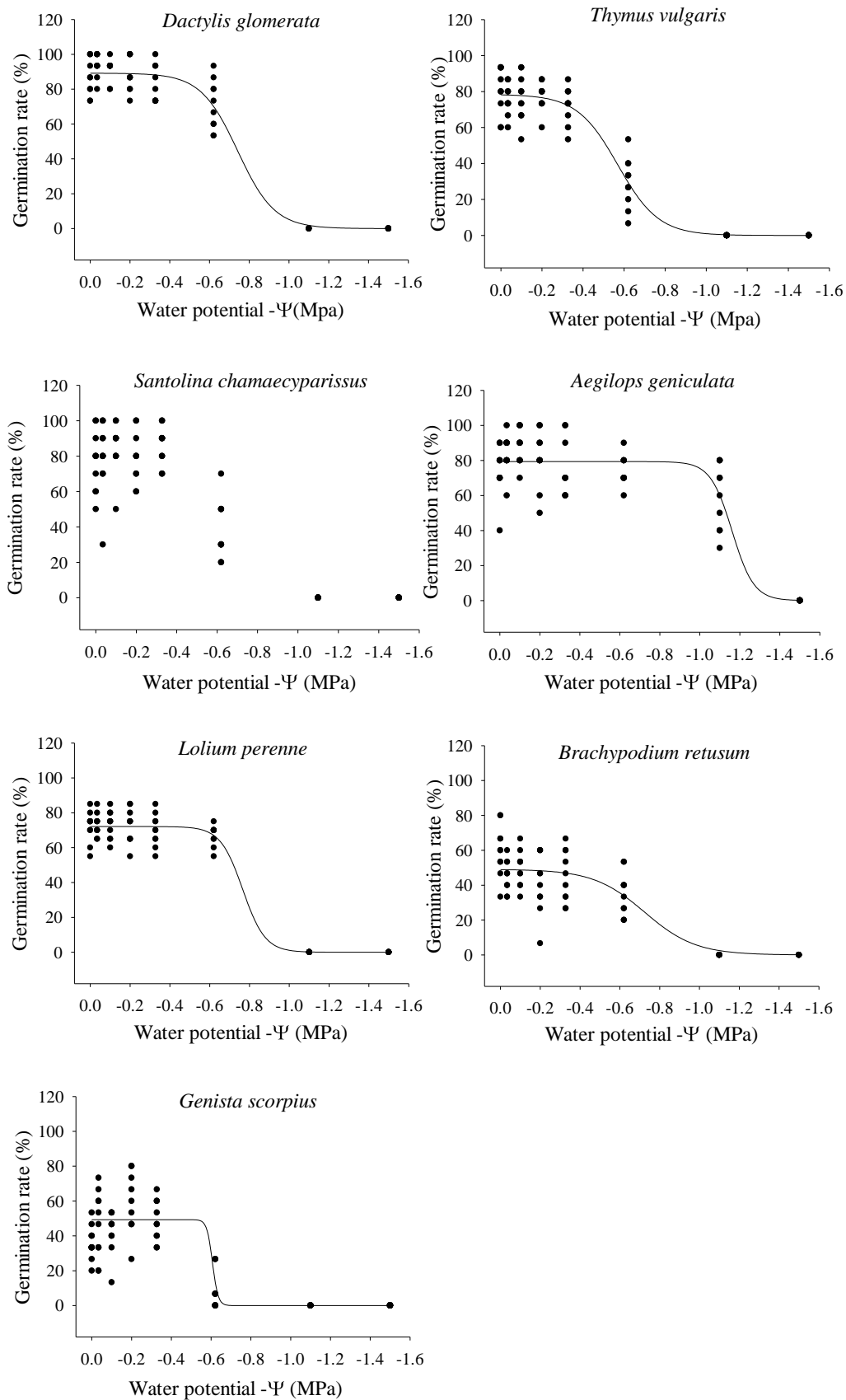
**Figure 5**



**Figure 6**



## Appendix B



## Appendix C